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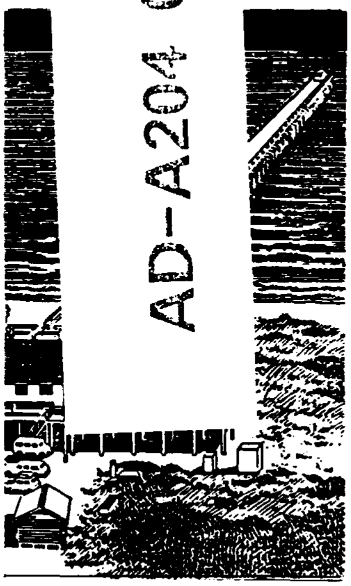

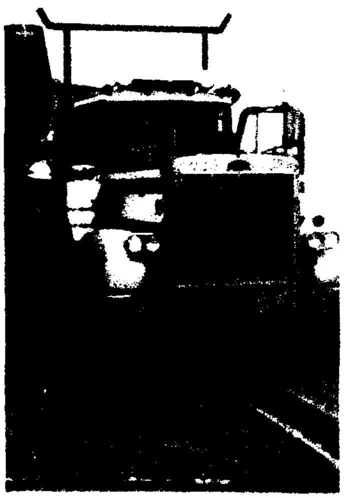

REPAIR, EVALUATION, MAINTENANCE, AND REHABILITATION RESEARCH PROGRAM

TECHNICAL REPORT REMR-CO-2

PROTOTYPE EXPERIENCE WITH THE USE OF DISSIMILAR ARMOR FOR REPAIR AND REHABILITATION OF RUBBLE-MOUND COASTAL STRUCTURES

by

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CS	Concrete and Steel Structures	EM	Electrical and Mechanical
GT	Geotechnical	EI	Environmental Impacts
HY	Hydraulics	OM	*Operations Management*
CO	Coastal		

COVER PHOTOS:

TOP — Field Research Facility, Duck, North Carolina.

BOTTOM — *Author delivers 42-ton dolos to Crescent City Harbor, California.*

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A survey of existing Corps structures that have used dissimilar armor for repair and rehabilitation was conducted. The survey was accomplished by search and study of project index maps, reconnaissance reports, special reports, and in conjunction with other work units and follow-up visits to the districts and divisions for first-hand discussions and observations. Results show that in all cases selection of the dissimilar armor type and weight was based on design guidance for new construction, prototype experience, engineering judgment, inferences from model tests of similar structure, or site-specific model tests rather than guidance specific to evaluating the interfacing and stability response of the dissimilar armor. It is reasonable to conclude that the guidance needed for use of dissimilar armor will become more critical in future years as rehabilitation of major breakwaters and jetties becomes necessary to extend their project life.

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PREFACE

Authority to carry out this investigation was granted the US Army Engineer Waterways Experiment Station's (WES's) Coastal Engineering Research Center (CERC) by the Office, Chief of Engineers (OCE), under Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program Work Unit 32325, "Use of Dissimilar Armor for Repair and Rehabilitation of Rubble-Mound Coastal Structures." The survey of field experience, which fulfills one milestone of this work unit, was conducted under general direction of Mr. James E. Crews and Dr. Tony C. Liu, REMR Overview Committee, OCE; Mr. Jesse A. Pfeiffer, Jr., Directorate of Research and Development, OCE; members of the REMR Field Review Group; Mr. John H. Lockhart, REMR Coastal Technical Monitor, OCE; and Messrs. William F. McCleese, REMR Program Manager, and D. D. Davidson, REMR Coastal Problem Area Leader, WES.

The study was conducted by personnel of CERC under general direction of Dr. James R. Houston, Chief, and Mr. Charles C. Calhoun, Jr., Assistant Chief, CERC; and under direct supervision of Mr. C. E. Chatham, Chief, Wave Dynamics Division, and Mr. Davidson, Chief, Wave Research Branch. Visitations to the US Army Corps of Engineers Division and District Offices to acquire survey data were made during the period February 1984 through September 1985 by Messrs. Dennis G. Markle and Robert D. Carver, Research Hydraulic Engineers; John P. Ahrens, Research Oceanographer; Peter J. Grace, R. Clay Baumgartner, and Frank E. Sargent, Hydraulic Engineers; Willie G. Dubose and Maury S. Taylor, Engineering Technicians; John M. Heggins, Computer Assistant; and Mrs. Lynette W. O'Neal, Engineering Aide. Field experience data were reviewed and this report was prepared by Mr. Carver.

Commander and Director of WES during report publication was COL Dwayne G. Lee, EN. Technical Director was Dr. Robert W. Whalin.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
feet	0.3048	metres
miles (US statute)	1.609344	kilometres
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic foot (pcf)	16.01846	kilograms per cubic metre
tons (2,000 lb. mass)	907.1847	kilograms

PROTOTYPE EXPERIENCE WITH THE USE OF DISSIMILAR ARMOR FOR REPAIR AND REHABILITATION OF RUBBLE-MOUND COASTAL STRUCTURES

PART I: INTRODUCTION

Background

1. There exists a lack of design guidance or information concerning the interfacing and stability response of armor units that are of dissimilar type and/or size. In the past, selection of new armor type, method of interfacing, and procedures for preparation of the existing section have been based on engineering judgment or, in more recent times, on site-specific model studies. Such studies have provided good singular solutions, but the data usually fail to meet the requirements of other projects. It is anticipated that the problem will become more acute in future years as rehabilitation of major breakwaters and jetties becomes necessary to extend their project life or to meet greater design demands.

Purpose

2. The primary objective of this report is to provide a summarized inventory of existing US Army Corps of Engineers (Corps) projects that have used dissimilar armor for repair and rehabilitation of rubble-mound coastal structures. These data will provide guidance in establishing research priorities to develop rehabilitation design information for dissimilar armor.

PART II: SURVEY METHODS AND RESULTS

Methods

3. The survey of existing Corps structures was accomplished by studying project index maps, reconnaissance reports, and special reports, and, in conjunction with other work units, follow-up visits to the districts and divisions for first-hand discussions and observations.

Results

4. Results of this survey, summarized in Table 1, show that of the 21 districts/divisions contacted, 5 have experience with the use of dissimilar armor. It should be noted that the majority of the districts which do not presently have dissimilar armor believe there is a potential future need as it becomes necessary to extend the project life of major breakwaters and jetties. For example, in the Great Lakes area it is becoming increasingly difficult to obtain properly shaped large size (>10 ton) stone for repair of laid-up stone breakwaters. Construction and rehabilitation histories of the eight projects currently using dissimilar armor are presented in Tables 2 through 9, and the following paragraphs describe characteristics of the projects.

Cleveland Harbor

5. Cleveland Harbor, Ohio, is located on the southern shore of Lake Erie at Cleveland, Ohio (Plate 1). Cleveland is located about 110 miles* east of Toledo, Ohio, and about 191 miles west of Buffalo, New York. The harbor is protected by a 20,970-ft east breakwater, 6,048-ft west breakwater, and two 1,250-ft arrowhead breakwaters. The arrowhead breakwaters are connected to the east and west breakwaters at the main entrance to the harbor (Plate 1). The westerly 3,000 ft of the east breakwater is composed of a timber crib, constructed from 1887 to 1900, and a stone superstructure, constructed from 1917 to 1926. The remaining 17,970 ft of the east breakwater was constructed from 1903-1915. This portion of the breakwater is a rubble-mound structure with a keyed and fitted system of specially shaped armor stone. Using

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* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 3.

construction similar to that in the original work, workmen made repairs on the east breakwater in the years 1927, 1928, 1930, 1932 to 1940, and 1946 to 1978. During 1980, the eastern 4,400 ft of the east breakwater was rehabilitated (Plate 2). Two layers of 2-ton unreinforced dolosse were placed on the lakeside of the trunk and around the east head (Plates 3 and 4, respectively); 29,700 dolosse were placed with a concentration of 161 dolosse per 25 lin ft of the breakwater. On 6 April 1982, a particularly severe storm (hindcast waves of 12 ft in height) occurred simultaneously with the highest lake level (+6.1 ft low water datum) ever recorded and caused damage to the rehabilitated dolos section. Although there was some displacement of dolosse over the crest of the trunk section, primary damage was localized on the tip of the head section where a hole about 20 ft in diameter at the armor surface penetrated to the original stone. The number of units broken due to displacement from the damage hole is not known, but total breakage on the entire dolos section after the April 1982 storm was reported as 487 or 1.6 percent of the units placed. A diver's survey indicated that the broken dolosse are generally in a zone 4 to 6 ft above and below the water level. The head section was repaired in September 1982 by placing approximately 200 dolosse in the localized damage area. Presently (1985), plans are being formulated for rehabilitation of an additional 3,300 ft of the east breakwater trunk using two layers of 9- to 20-ton armor stone (Plate 5). Table 2 summarizes the construction and rehabilitation history of the breakwater.

Crescent City Harbor

6. Crescent City Harbor, California, is located on the Pacific coast about 17 miles south of the Oregon-California border (Plate 6). The existing outer breakwater is 4,670 ft in length. The main stem and easterly extension (dogleg) of the breakwater are approximately 3,670 and 1,000 ft in length, respectively. The original project did not call for the dogleg but intended for the main stem of the breakwater to extend out to Round Rock. The main stem of the original breakwater, beyond sta 37+00, sustained severe damage and was reconstructed on two occasions. Finally, this portion of the main stem was abandoned, and the 1,000-ft dogleg referred to above was added. Two-dimensional stability tests were conducted of the tetrapod breakwater designs proposed for the trunk portion of the 1,000-ft dogleg (Hudson and Jackson 1955 and 1956). In 1957, 1,836 25-ton unreinforced tetrapods were placed on the sea-side slope from sta 41+20 to the end of the dogleg (sta 46+70), and 140

25-ton unreinforced tetrapods were stockpiled on the sea-side slope of the first 200 ft of the dogleg adjacent to the main stem (sta 37+00 to 39+00). Repair with dissimiliar armor first occurred in 1974 when 246 40-ton unreinforced dolosse were placed on the sea-side slope of the last 230 ft of the breakwater's main stem (sta 34+70 to 37+00). Various portions of the breakwater were repaired with armor stone in 1979. As of 1985, plans are being formulated for additional rehabilitation of the main stem of the breakwater (sta 34+70 to 37+00) with two layers of 42-ton fiber-reinforced concrete dolosse (Plate 7). This proposed work, together with the prior construction history, is summarized in Table 3.

Hilo Harbor

7. Hilo Harbor, Hawaii, the second largest harbor in the State of Hawaii, is located on the northeast coast of the Island of Hawaii (Plate 8). Construction of the 10,070-ft rubble-mound breakwater was completed in 1930. The tsunami of April 1946 produced a 1,100-ft long breach in the structure and severely damaged an additional 4,900-ft length with the average crown elevation being reduced to -3.0 ft mllw. Repair of damage caused by the 1946 tsunami was completed in 1948. Storms in 1951 and 1954 produced localized damage which was repaired in subsequent years. In 1960, another tsunami produced significant damage; however, no repair work was done until 1968 due to the possibility of totally rebuilding the breakwater as one leg of a proposed tsunami barrier for Hilo Harbor. Localized damage to various areas along the breakwater was repaired in 1973 and 1975. Dissimilar armor was first used in 1981. The sea side of the breakwater was repaired between sta 11+00 and 20+00 with one layer of uniformly-placed, 7.5-ton tribars. The construction and rehabilitation history of the breakwater is summarized in Table 4.

Humboldt Bay

8. Humboldt Bay, California, is located on the Pacific coast of northern California. The city of Eureka, about 280 miles north of San Francisco and about 80 miles south of Crescent City, California, is located on the northwest shore of Humboldt Bay (Plate 9). The Humboldt Bay entrance channel is protected by two rubble-mound jetties. Construction of the parallel north and south jetties, 4,500 and 5,100 ft long, respectively, was initiated in 1889 and completed in 1899. The original jetty construction was rubble-mound armor stone. Severe damage to the heads and portions of the trunks has required numerous rehabilitations and reconstructions of both jetties. Between

1911 and 1970, parapet walls, concrete caps, 20- and 100-ton concrete blocks, concrete monoliths, armor stone, and 12-ton tetrahedrons have been used on both jetties in an effort to stabilize the structures. Table 5 shows details of the construction history. In 1971 and 1972 both jetties were rehabilitated by reconstructing the concrete monoliths, placing 42-ton nominal cage-reinforced concrete dolosse around the seaward quadrant of the heads, and placing similiarly reinforced 43-ton dolosse on the shoreward transition sections of the heads. Spot damage to both jetties was repaired in 1985 using 42-ton fiber-reinforced concrete dolosse.

Kahului Harbor

9. Kahului Harbor, Maui, Hawaii, is located about 94 miles southeast of Honolulu, Hawaii, on the north coast of the Island of Maui (Plate 10). Two rubble-mound breakwaters provide protection for the harbor. The 2,766-ft east and 2,315-ft west breakwaters were completed in 1931. The heads of both breakwaters were severely damaged by storm waves in 1947, 1952, and 1954. In 1956 the breakwater heads were repaired by casting concrete monoliths on the crowns. The slopes of both heads and 250 ft of the west breakwater trunk (sea side only) were protected with a double layer of 33-ton unreinforced tetrapods; a total of 400 units was placed. A major storm in 1958 (approximately 34-ft breaking waves at breakwater heads) breached the trunk of the east breakwater and caused major damage on both heads. After the 1958 storm, emergency repairs were made on the east breakwater trunk using basalt armor stone, and model tests were initiated at the US Army Engineer Waterways Experiment Station (WES) (Jackson 1964) to determine the best methods of stabilizing the breakwaters. In 1966, a partial repair of the breakwaters was completed using 35- and 50-ton reinforced tribars. Also during the 1966 repair, a concrete rib cap was added to the crest of the east breakwater trunk. In 1969, 260 19-ton reinforced tribars and a concrete rib cap were added to the west breakwater trunk. This repair work, shoreward of the 33-ton tetrapod area, provided a partial repair of damages incurred by the structure during the December 1967 storm. In 1973 the sections of the west breakwater trunk were repaired using 19- and 35-ton reinforced tribars. The damaged 33-ton tetrapod areas of the west breakwater were repaired with 20- and 30-ton reinforced dolosse, and the east breakwater was rehabilitated with 6-ton unreinforced and 20- and 30-ton reinforced dolosse in 1977. The most recent rehabilitation (1982) used 11- and 25-ton tribars on the sea side, 6.5-ton tribars on the

harbor side of the west breakwater, and 9-ton tribars on the harbor side of the east breakwater. Table 6 summarizes the construction and rehabilitation history of the breakwaters.

Manasquan Inlet

10. Manasquan Inlet, New Jersey, is located on the Atlantic coast of New Jersey about 26 miles south of Sandy Hook in the boroughs of Manasquan and Point Pleasant Beach (Photo 1). The inlet forms the mouth of the Manasquan River and the northernmost end of the New Jersey Intracoastal Waterway. In 1880 the previously unnavigable inlet was dredged to provide access to a safe harbor for small vessels navigating along the coast. At the same time, sand-filled timber jetties were constructed out to 120 ft beyond the low-water line. The jetties proved to be ineffective in maintaining an open channel, and no maintenance was provided. By 1887, the inlet was totally blocked by sand. In 1930 the 1,230-ft north and 1,030-ft south rubble-mound jetties were constructed. Between 1931 and 1979, the jetties were rehabilitated nine times with progressively larger stone, culminating with placement of 12-ton stone. Dissimiliar armor rehabilitations using 16-ton, steel-reinforced dolosse were carried out on the south and north jetties in 1980 and 1984, respectively. The construction and rehabilitation history is summarized in Table 7.

Nawiliwili Harbor

11. Nawiliwili Harbor, Kauai, Hawaii, is located about 100 miles northwest of Honolulu, Hawaii, on the southeast coast of the Island of Kauai (Plate 11). Construction of the 2,150-ft rubble-mound stone breakwater was completed in 1930. Severe storms in 1954, 1956, and 1957 severely damaged the breakwater, and model tests were conducted in 1958 (Jackson, Hudson, and Housley 1960) to determine the best method of rebuilding the head and strengthening about 500 ft of the seaward end of the breakwater. In 1959 the head and seaward 500 ft of the sea-side slope of the trunk were rehabilitated with dissimiliar armor using 17.8-ton tribars, and a concrete cap was poured on the crest of the breakwater. Of the 598 tribars placed, 351 were reinforced. One layer of tribars was uniformly placed on the trunk, while two layers of randomly-placed tribars were used on the sea-side slope of the head. A survey of the breakwater in 1975 found varying deterioration of about 1,000 ft of the armor stone trunk and several slumped areas in the uniformly placed tribars. Hydraulic model tests (Davidson 1978) were conducted to aid in selection of the best rehabilitation method. Rehabilitation, completed in

1977, consisted of overlaying the uniformly placed tribars and the 300 ft of trunk shoreward of the tribar area with two layers of 11-ton unreinforced dolosse. Dolos coverage in the tribar area extended from the toe of the slope to +5.0 ft mllw, while the remaining 300 ft was overlaid from the toe to the structure's crown. Rehabilitation of the head with two layers of 23-ton dolosse was completed in 1985. The trunk was also rehabilitated using one layer of 11-ton dolosse on the sea-side slope and one layer of uniformly-placed, 6.5-ton tribars on the harbor-side slope (Plate 12). Construction history is summarized in Table 8.

San Pedro Breakwater

12. San Pedro Breakwater, Los Angeles, California, is one of three separate breakwaters that provides protection for the Ports of Los Angeles and Long Beach (Plate 13). Construction of the 11,150-ft breakwater was initiated in 1899 and completed in 1912 (Plate 14). In 1917 the 392-ft *S.S Governor* collided with the ocean side of the structure, displacing both substructure and superstructure stone along a 50-ft section. Repairs to the structure, completed in 1918, consisted of 1,000 tons of salvage stone and 200 tons of new stone. In 1941 wave-induced damage that occurred in 1939 was repaired. Although little information is available, it appears that the damage consisted of displaced dimension stones from the superstructure, and the repair work consisted of returning the dimension stones to their original positions. A storm on 21 March 1983 caused damage to the breakwater, including breaches of the superstructure at six locations as well as displacement of numerous dimension stones. The largest breach was 400 ft long, while the others varied form 20 to 80 ft. Based on results of model tests (Carver 1984), a molded concrete block repair section and a stone rubble-mound repair section that are more stable than the dimension stone section of the existing superstructure were developed. The stone rubble-mound repair option was chosen (first use of dissimilar armor on the breakwater); however, due to temporal constraints, the emergency repair section used in the large breach was considered temporary and differed significantly from the section developed in the model study. In 1984 about 12,000 tons of 7- to 20-ton capstone were placed in the major breach, and the smaller breaches were repaired using 1,600 tons of 7- to 20-ton capstone. Spot damage at numerous other locations was repaired by retrieving and replacing displaced dimension stone. Plans are being formulated to strengthen the major breach repair with additional 13- to 20-ton capstone, as shown in

Plate 15 (Baumgartner, Carver, Davidson, and Herrington 1986). Table 9 summarizes the construction and rehabilitation history of the breakwater.

PART III: CONCLUSION

13. Table 10 summarizes dissimilar armor usage by location, armor type and weight, placement date, and primary basis for armor selection. These data show that in all cases selection of the dissimilar armor type and weight was based on design guidance for new construction, prototype experience, engineering judgment, inferences from model tests of similar structures, or site-specific model tests rather than guidance specific to evaluating the interfacing and stability response of the dissimilar armor.

14. It is reasonable to conclude that the guidance needed for use of dissimilar armor will become more critical in future years as the cost of repairs increases and as rehabilitation of major breakwaters and jetties becomes necessary to extend their project life. Table 10 shows that almost half of the existing or proposed dissimilar armor applications have been implemented since 1980. The vast majority of existing Corps structures originally used stone armor; therefore, development of guidance for overlaying large existing armor stone with hydraulically superior units such as dolos and tribars is of great importance if we are to produce effective and economical rehabilitations and repairs. Further, the effects of mixing existing man-made armor should be investigated to assure major mistakes are not made and to produce new and efficient alternatives to conventional repairs.

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Table 1

Results of Survey for Dissimilar Armor Usage

Division	District	Findings* Positive	Findings* Negative
North Pacific (NPD)	Seattle (NPS)		X
	Portland (NPP)		X
	Alaska (NPA)		X
South Pacific (SPD)	San Francisco (SPN)	X	
	Los Angeles (SPL)	X	
Pacific Ocean (POD)	Honolulu (POH)	X	
Southwestern (SWD)	Galveston (SWG)		X
Lower Mississippi Valley (LMVD)	New Orleans (LMN)		X
South Atlantic (SAD)	Mobile (SAM)		X
	Jacksonville (SAJ)		X
	Savannah (SAS)		X
	Charleston (SAC)		X
	Wilmington (SAW)		X
North Atlantic (NAD)	Norfolk (NAO)		X
	Baltimore (NAB)		X
	Philadelphia (NAP)	X	
	New York (NAN)		X
New England (NED)			X
North Central (NCD)	Buffalo (NCB)	X	
	Detroit (NCE)		X
	Chicago (NCC)		X

* Positive: have existing Corps structures using dissimilar armor.
Negative: have *no* existing Corps structures using dissimilar armor.

Table 2

East Breakwater, Cleveland Harbor

Cleveland, OH

NCD, NCB

Date(s)	Construction and Rehabilitation History
1887-1900	Construction of 3,000 ft of east breakwater; timber crib construction.
1903-1915	Construction of 17,970 ft of east breakwater; keyed and fitted, specially shaped armor stone.
1917-1926	Addition of armor stone to the 3,000 ft of east breakwater previously constructed between 1887 and 1900.
1927 1928 1930 1932-1934 1936-1940 1946-1978	Repairs made to various reaches of the east breakwater during each of these years; original construction methods used in making repairs.
1980	Rehabilitation of 4,400 ft of eastern end of east breakwater (sta 230+00 to 274+00) using 29,500 2-ton unreinforced dolosse; two layers placed on lake side of trunk and around head using placement density of 161 dolosse per 25 lin ft of breakwater.
1982	Repair of head damage (April 1982 storm) using 200 2-ton unreinforced dolosse.
1985	Rehabilitation of an additional 3,300 ft of east breakwater trunk; two layers of 9- to 20-ton armor stone to be placed on the sea-side slope (model-tested, Markle and Dubose 1985).

NOTE: Design Storm Conditions. 8.8-sec, 13.4-ft nonbreaking waves; a 1-in-20-year occurrence wave, plus a 10-year maximum monthly mean lake level plus a short-term lake level fluctuation used resulting in a 1-in-200-year event assuming all events independent.

Maximum Storm Condition Exposure. 12-ft waves hindcast from April 1982 storm wind data.

Table 3

Outer Breakwater, Crescent City Harbor

Crescent City, California

SPD, SPN

Date(s)	Construction and Rehabilitation History
1930	Construction of 3,000-ft main stem of breakwater (sta 0+00 to 30+00); armor stone.
1948	Construction of 1,000-ft extension of main stem (sta 30+00 to 40+00); armor stone.
1949	Repair of main stem (sta 30+00 to 40+00) and extension of main stem to sta 42+00; armor stone.
1950	Repair of main stem (sta 30+00 to 42+00) using armor stone and addition of concrete cap to crown of breakwater except for area between sta 12+34 and 15+34.
1957	500 ft of main stem (sta 37+00 to 42+00) abandoned; addition of 1,000-ft dogleg (sta 37+00 to 47+70); 12-ton stone protection used from sta 37+00 to 41+20; beginning at sta 41+20, two layers of 25-ton unreinforced tetrapods (1,836 units) placed on sea-side slope (model tested, Hudson and Jackson 1955, 1956) and around head of dogleg; 140 of same size tetrapods placed on existing stone armor protection of sea-side slope of first 200 ft of dogleg adjacent to main stem(sta 37+00 to 39+00). These 140 tetrapods not placed in coherent two layers, and this area of repair not model tested.
1974	Rehabilitation of main stem of breakwater (sta 34+70 to 37+00); two layers of 40-ton unreinforced dolosse (246 units) placed on sea-side slope (not model tested).
1979	Repair of following reaches using 18- to 30-ton stone: sta 19+00 to 20+00, sta 22+00 to 24+00, sta 24+60 to 27+20, sta 28+90 to 29+50, sta 30+50 to 31+00, and sta 37+00 to 41+20; sta 15+50 to 17+50 repaired using 14- to 25-ton stone (none of the above model tested).
1986	Additional rehabilitation of main stem of breakwater (sta 34+70 to 37+00); two layers of 42-ton fiber-reinforced concrete dolosse (about 450 units) to be placed on sea-side slope (model tested, Baumgartner, Carver, and Davidson 1985).

NOTE: Design Storm Condition. 21- to 35-ft breaking waves (1-in-100-year occurrence).

Maximum Storm Condition Exposure. Design conditions.

Table 4

Hilo Breakwater

Hilo Harbor, Hawaii, Hawaii

POD, POH

Date(s)	Construction and Rehabilitation History
1930	Corps completed 10,070-ft-long rubble-mound breakwater.
1946	Tsunami of April 1946 severely damaged 6,000 ft of the breakwater; primary armor stone and core material displaced both seaward and toward the harbor down to an average elevation of -3.0 ft mllw; 1,100-ft-long breech occurred.
1946-1948	Tsunami damage repaired using original design criteria.
1949-1952	Storm waves of December 1951 caused damage to 13 areas. By October 1952 structure repaired to original cross section.
1954-1957	Storm waves of March 1954 caused damage to several areas. By August 1957 structure repaired to original cross section. Structure exposed to tsunami of 9 March 1957 but sustained no apparent damage.
1960-1967	Tsunami of 1960 produced significant damage; however, no work done between 1960 and 1967 due to possibility of totally rebuilding breakwater as one leg of a proposed tsunami barrier for Hilo Harbor.
1968	Repair work completed in August 1968; 11 areas repaired. Due to severity of wave overtopping and the recurrence of damage in many years, armor stone weight used for repair of crown increased from a minimum of 8 tons to a minimum of 10 tons. Remainder of repair work followed original cross-section design.
1971-1973	An inspection of 7 April 1971 revealed deterioration of structure at various points along entire length; immediate repair of 1,700 ft of the shoreward end of structure needed to protect the berthing area. Emergency repair work completed in 1973; original cross section design used for repair.

(Continued)

NOTE: Design Storm Conditions. 1981 tribar repair not model tested but used 13.5-ft breaking waves in water depth of 15.5 ft and stability coefficient of 7.5; design conditions for remainder of structure unknown.

Maximum Storm Condition Exposure. Wave height unknown, but old stone structure exposed to large wave conditions on a regular basis.

Table 4 (Concluded)

Date(s)	Construction and Rehabilitation History
1975	Major repair of breakwater completed. Both new and reset 8-ton and 10-ton minimum weight armor stones used to repair various areas along entire length of structure. Structure slopes and crown elevation unchanged from original design cross section.
1981	Breakwater repaired between sta 11+00 and 20+00. One layer of uniformly placed 7.5-ton tribars extended from sea-side toe to crown on a 1V on 1.5H slope. A total of 1,020 tribars placed (not model tested). The tribar toe buttressed with a single row of 8- to 12-ton stone and concrete ribs constructed on the crown. Design based on a 15.5-ft water depth, breaking wave height of 13.5 ft, and a K_D of 7.5.

Table 5

North and South Jetties, Humboldt Bay

Eureka, California

SPD, SPN

Date(s)	Construction and Rehabilitation History
1889-1899	Construction of 4,500-ft north jetty and 5,100-ft south jetty; armor stone.
1911-1915	Reconstruction of south jetty; armor stone.
1915-1916	Concrete monolith (1,000 tons) added to seaward end of south jetty.
1915-1925	Reconstruction of north jetty, armor stone; 1,050-ton concrete monolith added to seaward end.
1925-1927	Parapet walls and concrete caps added to crests of both jetties and mass concrete poured on channel slopes to stabilize armor stone.
1930-1958	Rehabilitation of both jetties. Mass concrete poured to fill eroded areas on crests; armor stones replaced in areas breached and washed out. Both 100-ton concrete blocks (number not known) and 12-ton tetrahedons (number not known) placed on heads of both jetties during this period.
1960-1963	Rehabilitation of both jetties. Trunks repaired with 12-ton stone; reconstruction of heads using 20-ton concrete blocks to form perimeter of heads and centers filled with mass concrete; 100-ton concrete blocks (250 total) placed around seaward tip of south jetty head.
1971-1972	Rehabilitation of both jetties (model tested, Davidson 1971); concrete monoliths reconstructed; 42-ton dolosse placed around seaward quadrant of both jetty heads (4 unreinforced, 1,271 steel-reinforced, and 17 steel fiber-reinforced dolosse on north jetty, and 22 unreinforced and 1,423 steel-reinforced dolosse on south jetty); 43-ton dolosse placed on the shoreward-transition sections of both jetty heads (967 and 1,090 steel-reinforced dolosse placed on north and south jetties, respectively); two layers of dolosse placed using a concentration of 11 dolosse per 1,000 sq ft of slope.
1986	Repair of spot damage to both jetties using 42-ton fiber reinforced dolosse (not model tested).

NOTE: Design Storm Conditions. 16-sec, 40-ft breaking waves.

Maximum Storm Condition Exposure. No recorded data but design conditions probable.

Table 6

East and West Breakwaters, Kahului Harbor

Kahului, Maui, Hawaii

POD, POH

Date(s)	Construction and Rehabilitation History
1931	Construction of 2,766-ft east breakwater and 2,315-ft west breakwater; armor stone.
1956	Repair of breakwater heads and 250 ft of west breakwater trunk; concrete monoliths poured on crests of heads; two layers of 33-ton unreinforced tetrapods (400 units total) placed on slopes of heads and sea-side slope of west breakwater trunk.
1958	Emergency repair of breach in east breakwater trunk; armor stone.
1966	Repair of both breakwater heads and first 355 ft shoreward of east breakwater head; one layer of 35-ton tribars placed and overlaid with one layer of 50-ton tribars on inboard quadrants of the breakwater heads; two layers of 35-ton tribars placed on sea-side slope of the east breakwater head and buttressed against concrete rib cap constructed on the crest; 827 and 181 35-ton reinforced tribars placed on east and west breakwaters, respectively; 43 and 173 50-ton reinforced tribars placed on east and west breakwaters, respectively. Except for concrete rib cap, all repair work model tested (Jackson 1964).
1969	Repair of west breakwater trunk; two layers of 19-ton reinforced tribars (260 units) placed on sea-side slope shoreward of tetrapod armor area. Concrete rib cap added to crest for buttressing of the tribars (repairs not model tested).
1973	Repair of west breakwater trunk; area rehabilitated in 1969 repaired and extended slightly using 80 19-ton reinforced tribars; 25 35-ton reinforced tribars placed adjacent to and on shoreward end of this area. Acute angle of wave attack occurring in this area tended to displace 19-ton tribars shoreward, and 35-ton tribars added as a buttress for the smaller units (repairs not model tested).

(Continued)

NOTE: Design Storm Conditions. 18-sec, 34-ft breaking waves (1-in-25-year occurrence).

Maximum Storm Condition Exposure. Observed design conditions in 1947 and again in 1954; thereafter, no recorded observations but design conditions probable.

Table 6 (Concluded)

Date(s)	Construction and Rehabilitation History
1977	Repair of west breakwater head and trunk; 257 30-ton and 291 20-ton reinforced dolosse placed (two layers over the 33-ton tetrapods) on sea-side quadrant of head and sea-side slope of trunk, respectively (not model tested).
1977	Repair of east breakwater head and trunk; 610 30-ton reinforced dolosse placed in a double layer over 33-ton tetrapods on seaward quadrant of the head; 164 20-ton reinforced dolosse placed in a double layer on sea-side slope of trunk beginning at the shoreward end of the 35-ton tribars. Beginning at the point where the 20-ton dolosse ended and extending shoreward, two layers of 6-ton unreinforced dolosse placed (455 units) on sea-side slope of the trunk (repairs not model tested).
1982	Rehabilitation of sea- and harbor-side slopes and crown of the west breakwater trunk; 170 11-ton unreinforced tribars placed on sea-side slope between sta 17+75 and sta 19+48; 10 25-ton tribars placed as a buttress on the shoreward side of the 11-ton tribars (sta 17+50 to sta 17+75); 540 6.5-ton unreinforced tribars placed on harbor side slope between sta 17+75 and sta 22+38. Concrete rib cap added to crown between sta 17+75 and sta 19+35. Rehabilitation of the east breakwater harbor-side slope and crown; 755 9-ton tribars placed on harbor-side slope (sta 19+50 to sta 27+80); concrete ribs added to crown (sta 19+50 to sta 23+80). All tribars used one layer uniform placement. Rehabilitation work model tested (Markle 1982).

Table 7

South and North Jetties, Manasquan Inlet

Point Pleasant, New Jersey

NAD, NAP

Date(s)	Construction and Rehabilitation History
1980	Inlet opened and sand-filled timber jetties constructed out to 120 ft beyond low-water line (not model tested).
1981-1887	No maintenance carried out and by 1887 inlet totally blocked by sand.
1899	Repair of north jetty.
1930	Construction of 1,900 lin ft of steel sheet-pile bulkheads, 1,230-ft north jetty, and 1,030-ft south jetty. Both jetties rubble-mound structures.
1931-1979	Jetties rehabilitated nine times with progressively larger stone (none model tested). Last effort used 12-ton stone.
1980	Rehabilitation of south jetty (not model tested); 680 16-ton steel-reinforced dolosse placed on outer 400 ft of channel-side slope, around the head, and 50 ft of beach-side slope. Dolosse placed from toe to crown with a concentration of 23 dolosse per 1,000 sq ft of surface area. First layer of dolosse placed with the vertical fluke downslope and random placement used in second layer.
1984	Rehabilitation of north jetty (not model tested) using 646 16-ton steel-reinforced dolosse placed on head and sea-side slope of trunk.

NOTE: Design Storm Conditions. 13-sec, 25-ft breaking waves (1-in-50-year occurrence).

Maximum Storm Condition Exposure. During March 1984 21-ft waves measured in 50-ft depth; condition assumed to have produced design wave heights at the structure.

Table 8

Breakwater, Nawiliwili Harbor

Nawiliwili, Kauai, Hawaii

POD, POH

Date(s)	Construction and Rehabilitation History
1930	Construction of 2,150-ft rubble-mound stone breakwater.
1959	Rehabilitation of head and outer 500 ft of trunk (model tested, Jackson, Hudson, and Housley 1960); two layers of 17.8-ton tribars randomly-placed on sea-side slope of head and one layer of 17.8-ton tribars uniformly placed on sea-side slope of trunk; 351 of 598 tribars placed were reinforced; concrete cap and reinforced concrete posts added to crown of breakwater in rehabilitated area.
1977	Rehabilitation of one layer of tribars and 300 ft of trunk shoreward of this area (model tested, Davidson 1978); 485 11-ton unreinforced dolosse (two layers) placed from toe to approximately +5.0 ft mllw over one layer tribar area; 449 11-ton unreinforced dolosse (two layers) placed on the sea-side slope of the trunk for 300 ft shoreward of the tribar area. Dolosse in this area placed from toe to crown of structure.
1986	Rehabilitation of head using two layers of 23-ton dolosse. Trunk rehabilitated with one layer of 11-ton dolosse on sea-side slope (sta 18+35 to 20+45), one layer of uniformly-placed 6.5-ton tribars on the harbor-side slope (sta 12+00 to 15+00), and construction of concrete ribs on the crown (sta 12+00 to 20+45). Work model tested (Markle and Herrington 1983).

NOTE: Design Storm Condition

a. Trunk: 12-sec, 19.4-ft breaking waves (1-in.-5-year occurrence).
b. Head: 15-sec, 24-ft breaking waves (1-in.-5-year occurrence).

Maximum Storm Condition Exposure. Hurricane Iwa (Nov 1982) estimated to have produced design wave conditions.

Table 9

San Pedro Breakwater, Los Angeles, California

SPD, SPL

Date(s)	Construction and Rehabilitation History
1912	Construction of the 11,150-ft-long dimensioned stone breakwater completed.
1917	Ship collision damaged a 50-ft section of structure.
1918	Damage from ship collision repaired using 1,000 tons of salvage stone and 200 tons of new stone.
1941	Wave-induced damage that occurred in 1939 repaired by returning displaced dimension stones to original positions.
1983	Storm on 21 March 1983 caused damage, including breaches of superstructure at six locations as well as displacement of numerous dimension stone. Largest breach 400 ft long; smaller breaches varied from 20 to 80 ft.
1984	Breaches repaired with 7- to 20-ton angular shaped capstone (first use of dissimilar armor) and spot damage repaired by retrieving and replacing displaced dimension stone.
1986	Major breach repair with additional 13- to 20-ton capstone (model tested, Baumgartner, Carver, Davidson, and Herrington, 1986).

NOTE: Design Storm Conditions. Original design condition unknown.

Maximum Storm Condition Exposure. Storm of 21 March 1983 produced 8- to 16-sec, 15.6-ft nonbreaking waves.

Table 10

Summary of Dissimilar Armor Usage

Location	Dissimilar Armor Type	Dissimilar Armor Weight Tons	Date Placed	Primary Basis for Selection
East Breakwater, Cleveland Harbor Inlet, New Jersey	Dolos	2	1980	Other*
	Stone	9-20	1985	Model tests
Outer Breakwater, Crescent City Harbor, California	Dolos	40	1974	Other
	Dolos	42	1986	Model tests
Hilo Breakwater, Hilo Harbor, Hawaii	Tribar	7.5	1981	Other
North and South Jetties, Humboldt Bay, California	Block	100	1930-1958	Other
	Tetrahedron	12	1930-1958	Other
	Cube	100	1965	Other
	Dolos	42-43	1971-1972	Model tests
	Dolos	42	1986	Other
East Breakwater, Kahului Harbor, Maui, Hawaii	Tetrapod	33	1956	Other
	Tribar	35	1966	Model tests
	Tribar	50	1966	Model tests
	Dolos	6	1977	Other
	Dolos	20	1977	Other
	Dolos	30	1977	Other
	Tribar	9	1982	Model tests
West Breakwater, Kahului Harbor, Maui, Hawaii	Tetrapod	33	1956	Other
	Tribar	35	1966	Model tests
	Tribar	50	1966	Model tests
	Tribar	19	1969	Other
	Tribar	19	1973	Other
	Tribar	35	1973	Other
	Dolos	20	1977	Other
	Dolos	30	1977	Other
	Tribar	6.5	1982	Model tests
	Tribar	11	1982	Model tests
	Tribar	25	1982	Model tests

(Continued)

* "Other" includes design guidance for new construction, prototype experience, engineering judgment, and inferences from model tests of similar structures.

Table 10 (Concluded)

Location	Dissimilar Armor Type	Dissimilar Armor Weight Tons	Date Placed	Primary Basis for Selection
South and North Jetties, Manasquan Inlet, New Jersey	Dolos	16	1980	Other
	Dolos	16	1984	Other
Breakwater, Nawiliwili Harbor, Kauai, Hawaii	Tribar	17.8	1959	Model tests
	Dolos	11	1977	Model tests
	Tribar	6.5	1986	Model tests
	Dolos	11	1986	Model tests
	Dolos	23	1986	Model tests
San Pedro Breakwater, Los Angeles, California	Stone	7-20	1984	Model tests and Expediency
	Stone	13-20	1986	Model tests

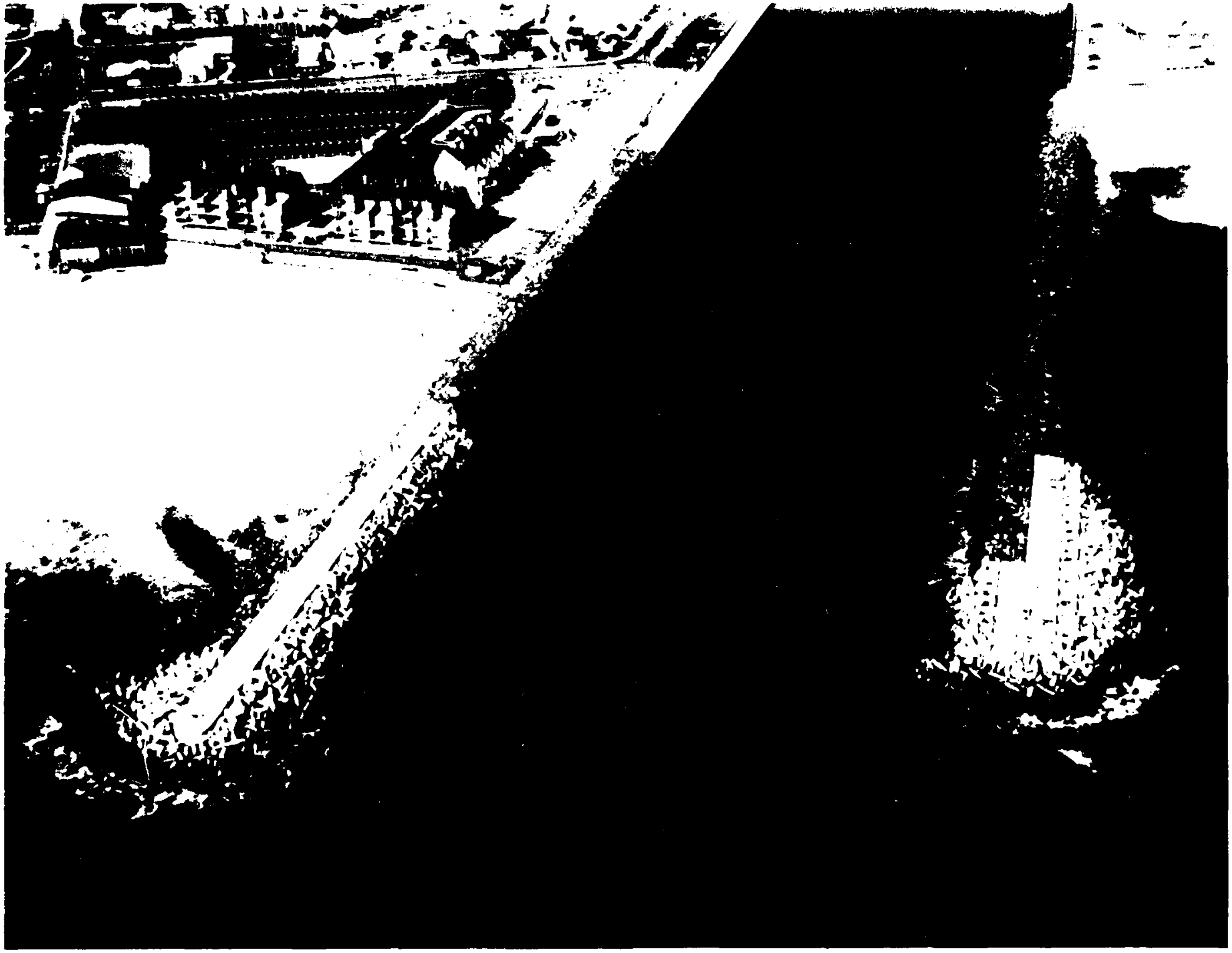
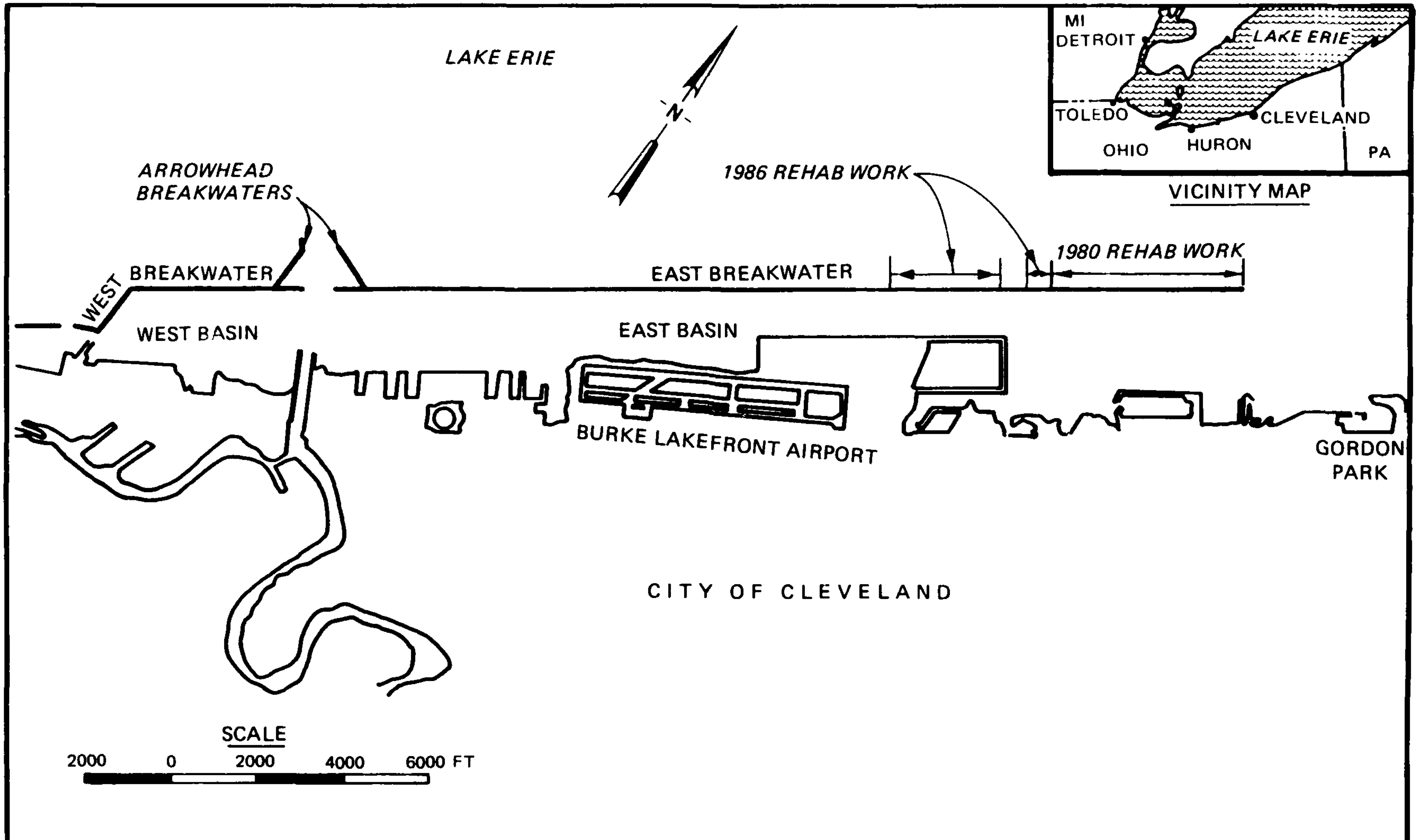


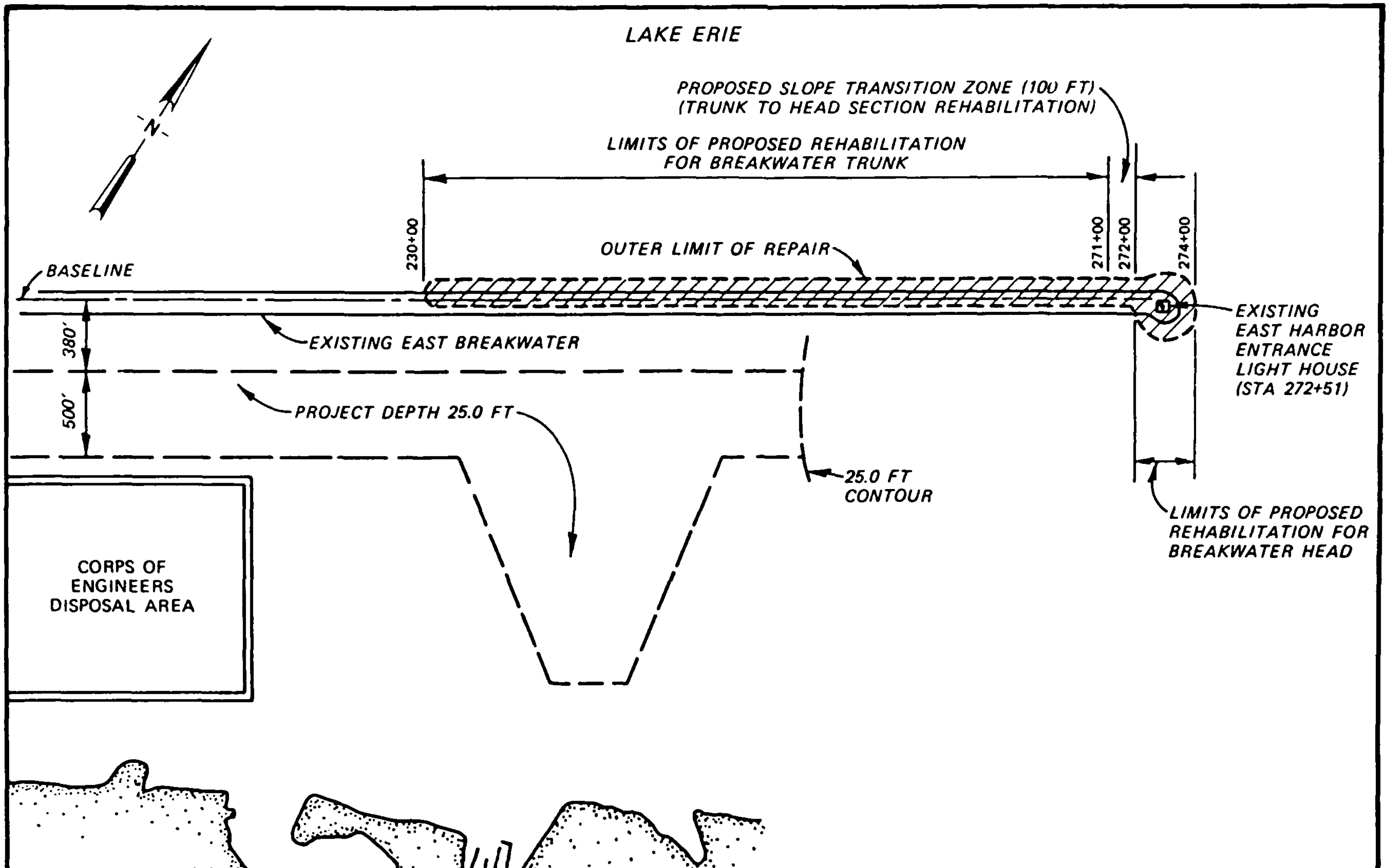
Photo 1. Manasquan Inlet, New Jersey



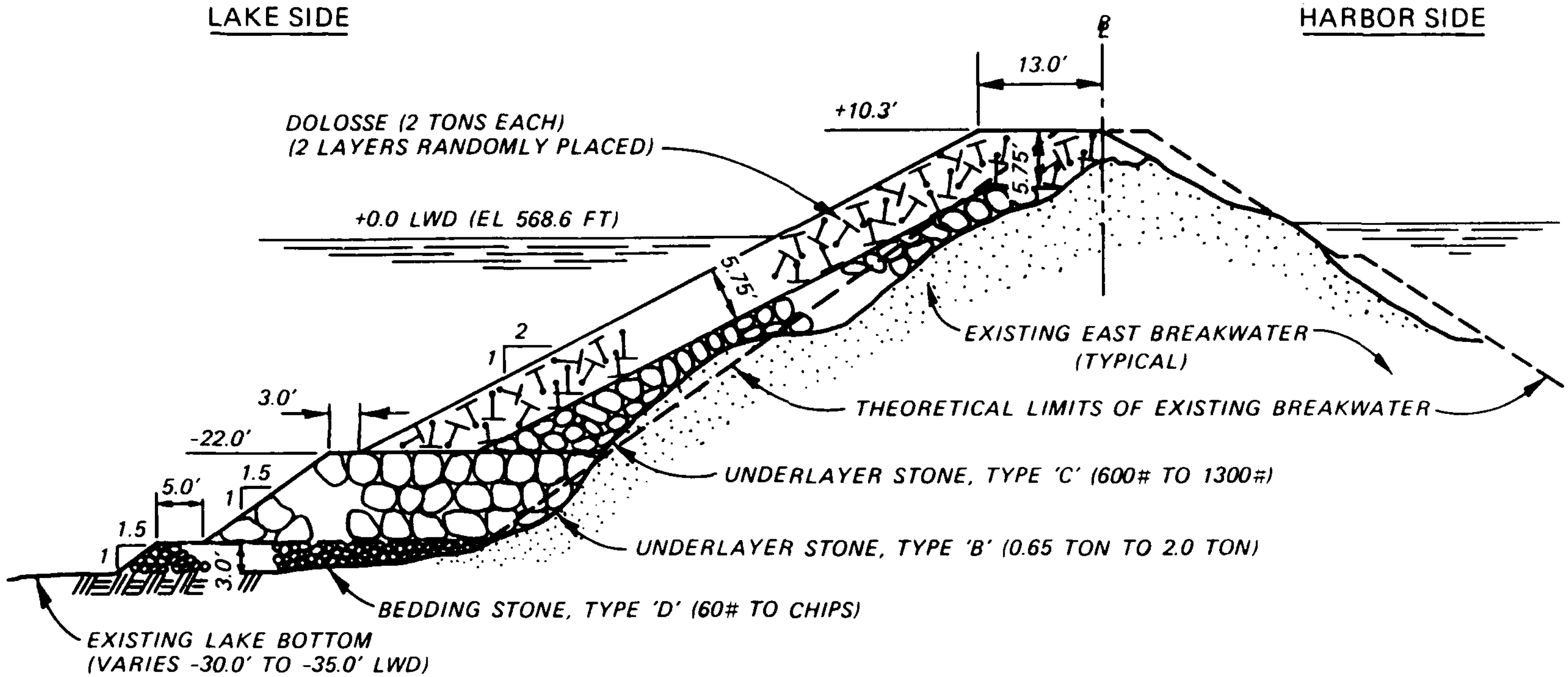
CLEVELAND BREAKWATERS
LOCATION MAP

PLATE 1

PLATE 2

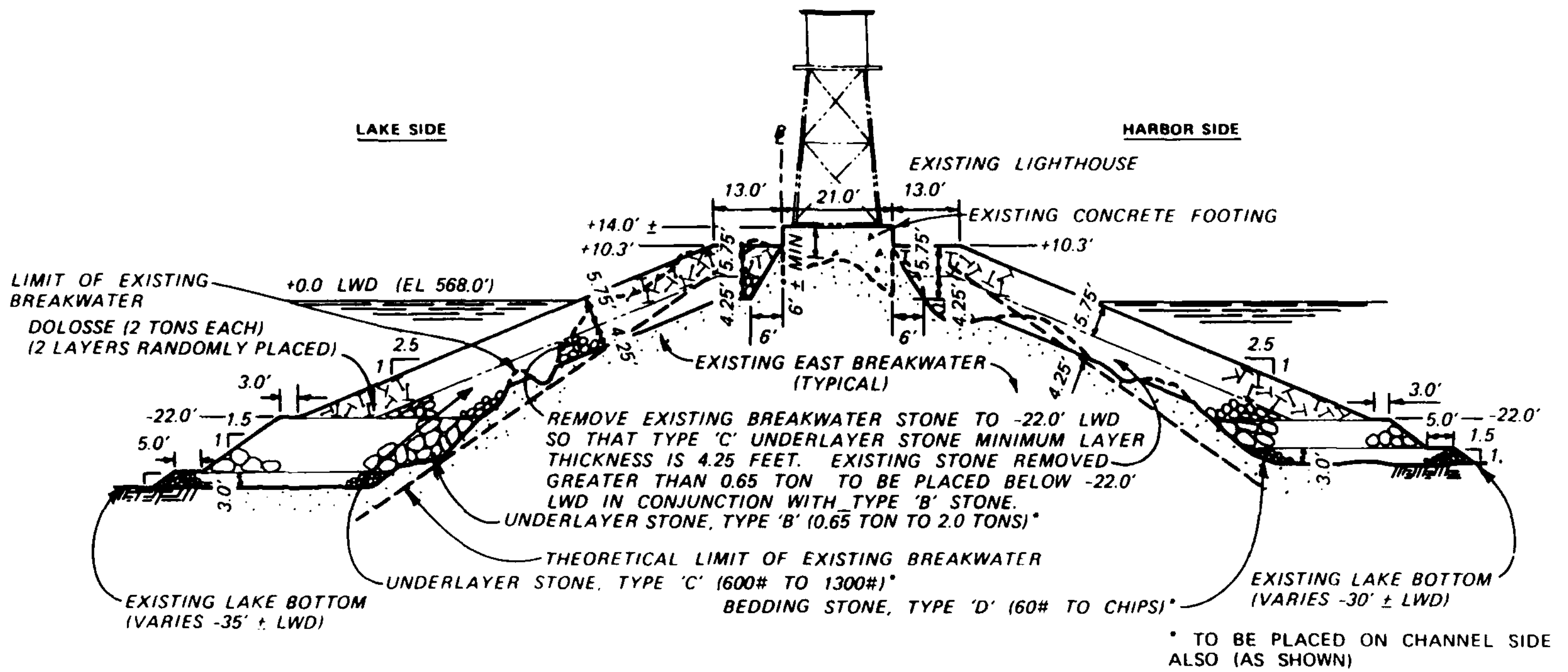


CLEVELAND HARBOR EAST BREAKWATER
1980 REHABILITATION



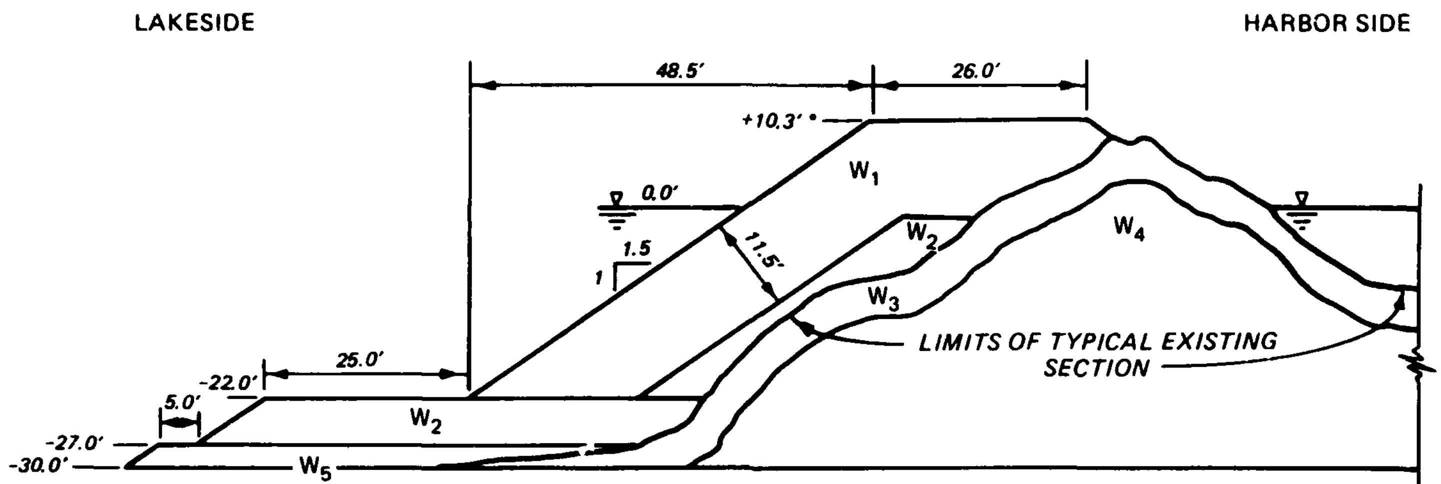
SECTION OF BREAKWATER TRUNK

**CONCRETE ARMOR UNIT DESIGN,
BREAKWATER TRUNK
(CLEVELAND HARBOR EAST BREAKWATER
1980 REHABILITATION)**



SECTION OF BREAKWATER HEAD

CONCRETE ARMOR UNIT DESIGN, BREAKWATER HEAD (CLEVELAND HARBOR EAST BREAKWATER 1980 REHABILITATION)



MATERIAL CHARACTERISTICS

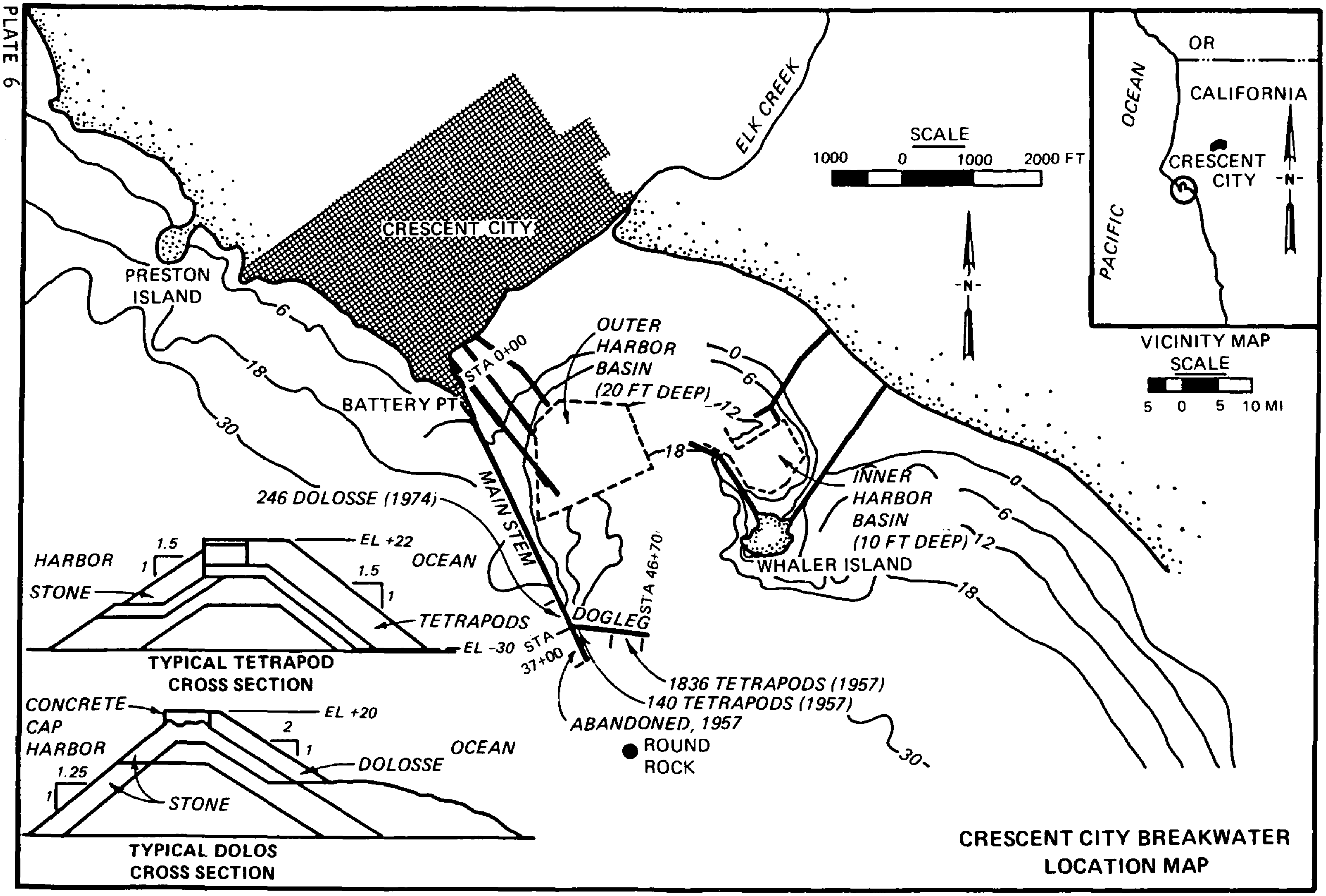
MODEL

** † W_1 = 0.61- TO 1.35-LB STONE @ 165 PCF
** W_2 = 0.044- TO 0.135-LB STONE @ 165 PCF
†† W_3 = 0.202- TO 0.541-LB STONE @ 165 PCF
$W_4 \leq$ 0.135-LB STONE @ 165 PCF
** $W_5 \leq$ 0.001-LB STONE @ 165 PCF
* ELEVATION IN FEET REFERRED TO LWD
** REHABILITATION MATERIALS
† TWO LAYERS; RANDOM PLACEMENT
†† ONE LAYER; LAID UP PLACEMENT

PROTOTYPE

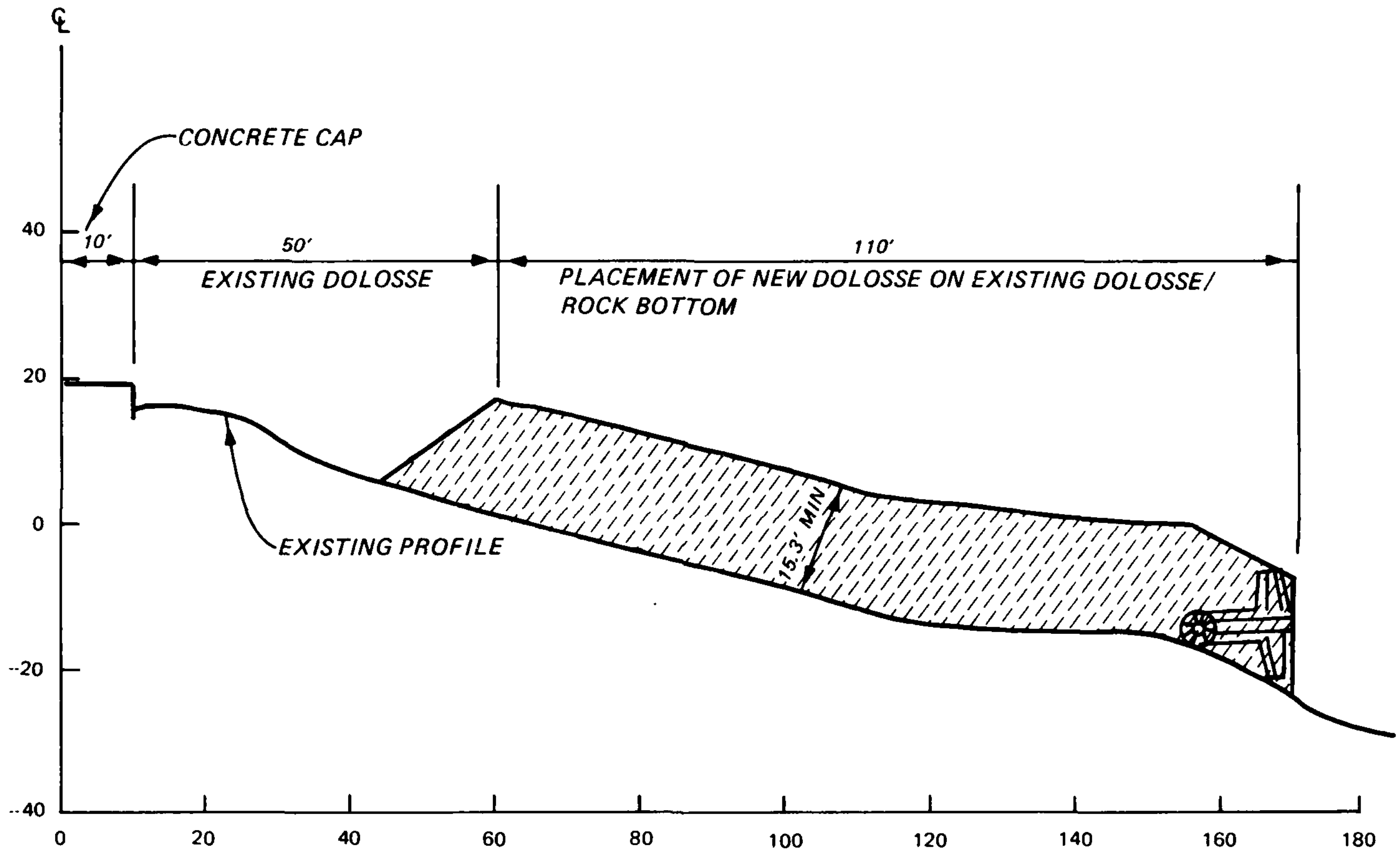
W_1 = 18,000- TO 40,000-LB STONE @ 155 PCF
W_2 = 1,300- TO 4,000-LB STONE @ 155 PCF
W_3 = 6,000- TO 16,000-LB STONE @ 155 PCF
$W_4 \leq$ 4,000-LB STONE @ 155 PCF
$W_5 \leq$ 60-LB STONE @ 155 PCF

TYPICAL SECTION
CLEVELAND HARBOR BREAKWATER
1985 REHABILITATION
9-TO-20-TON ARMOR STONE

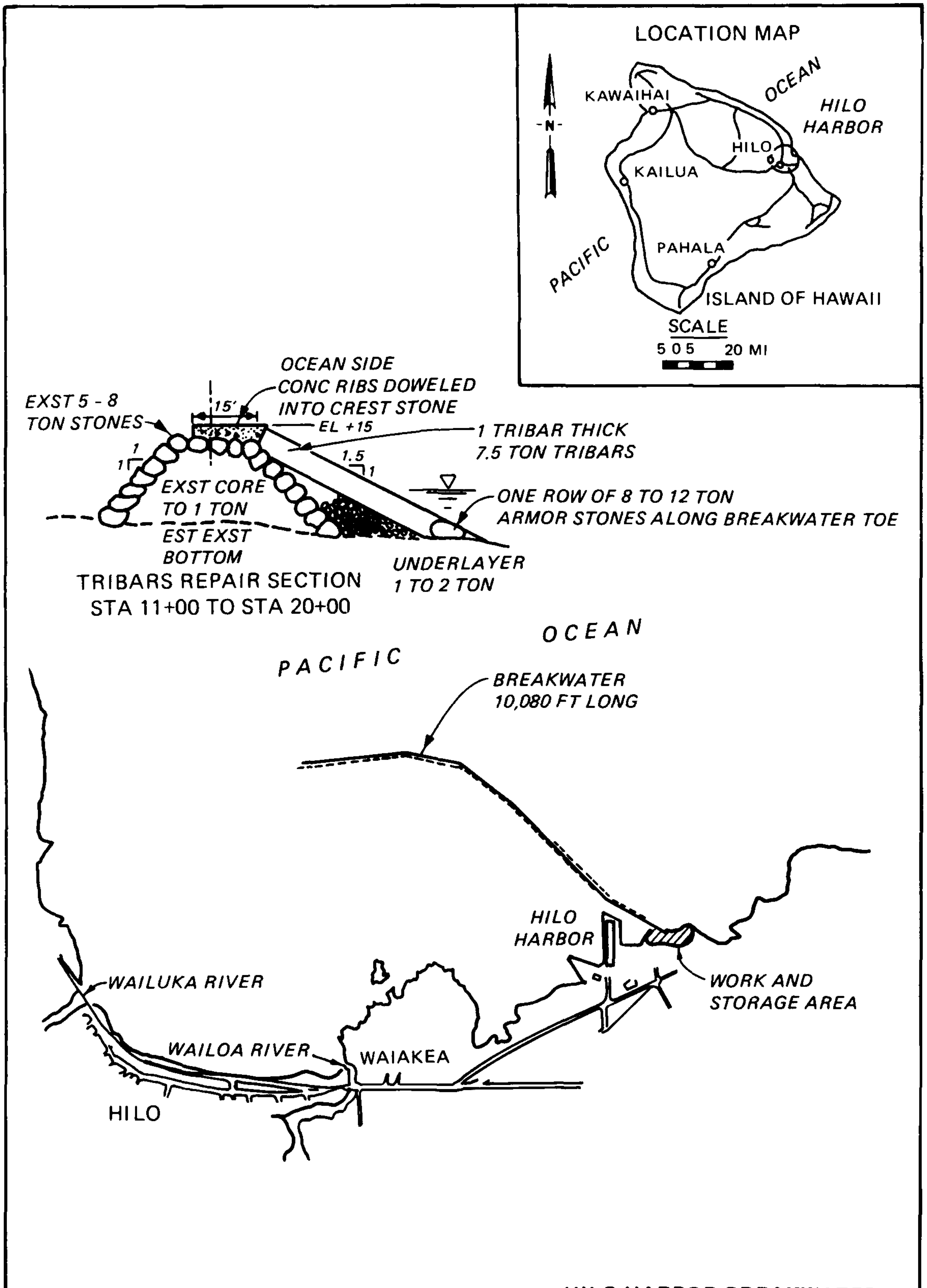


CRESCENT CITY BREAKWATER LOCATION MAP

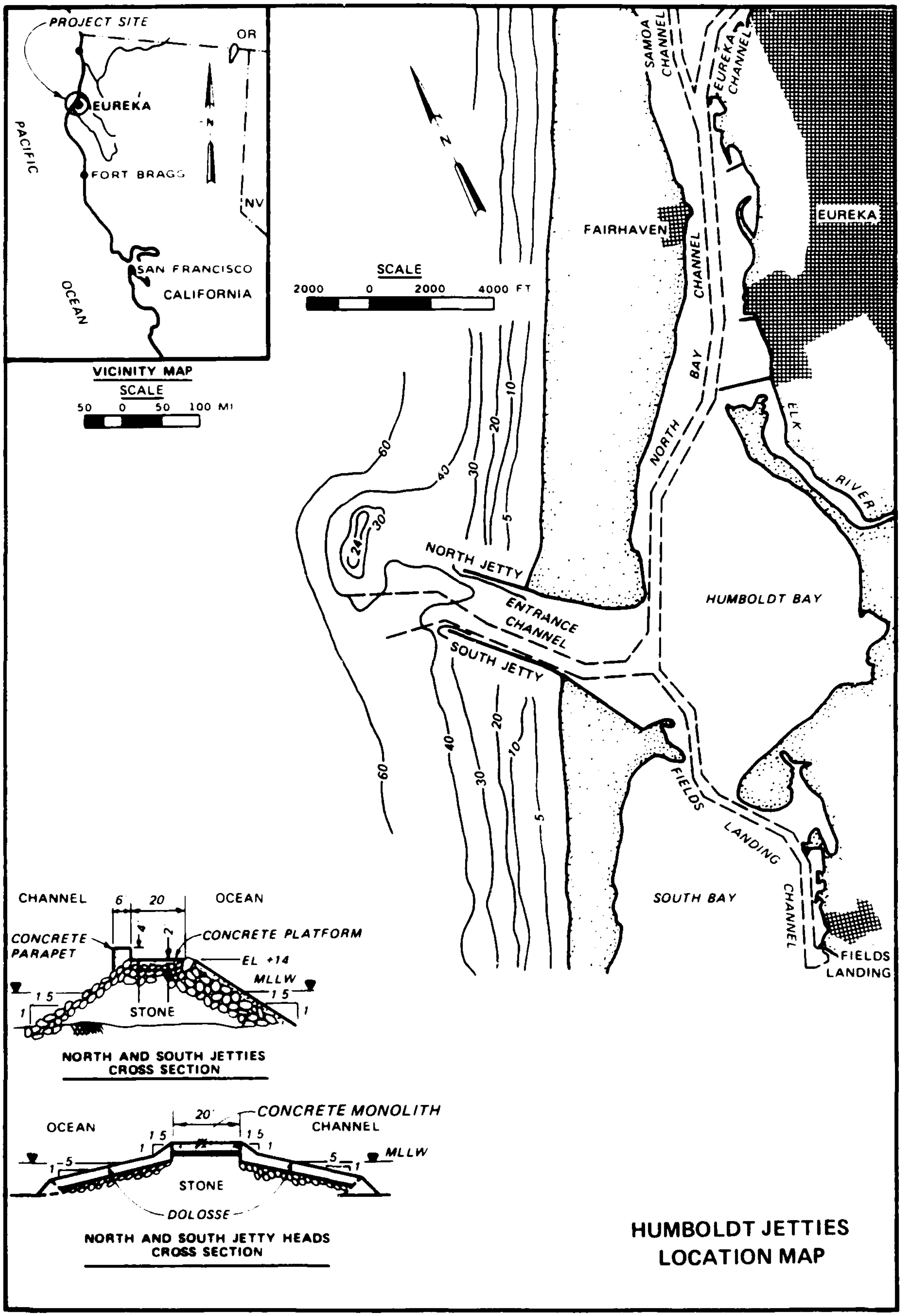
PLATE 6



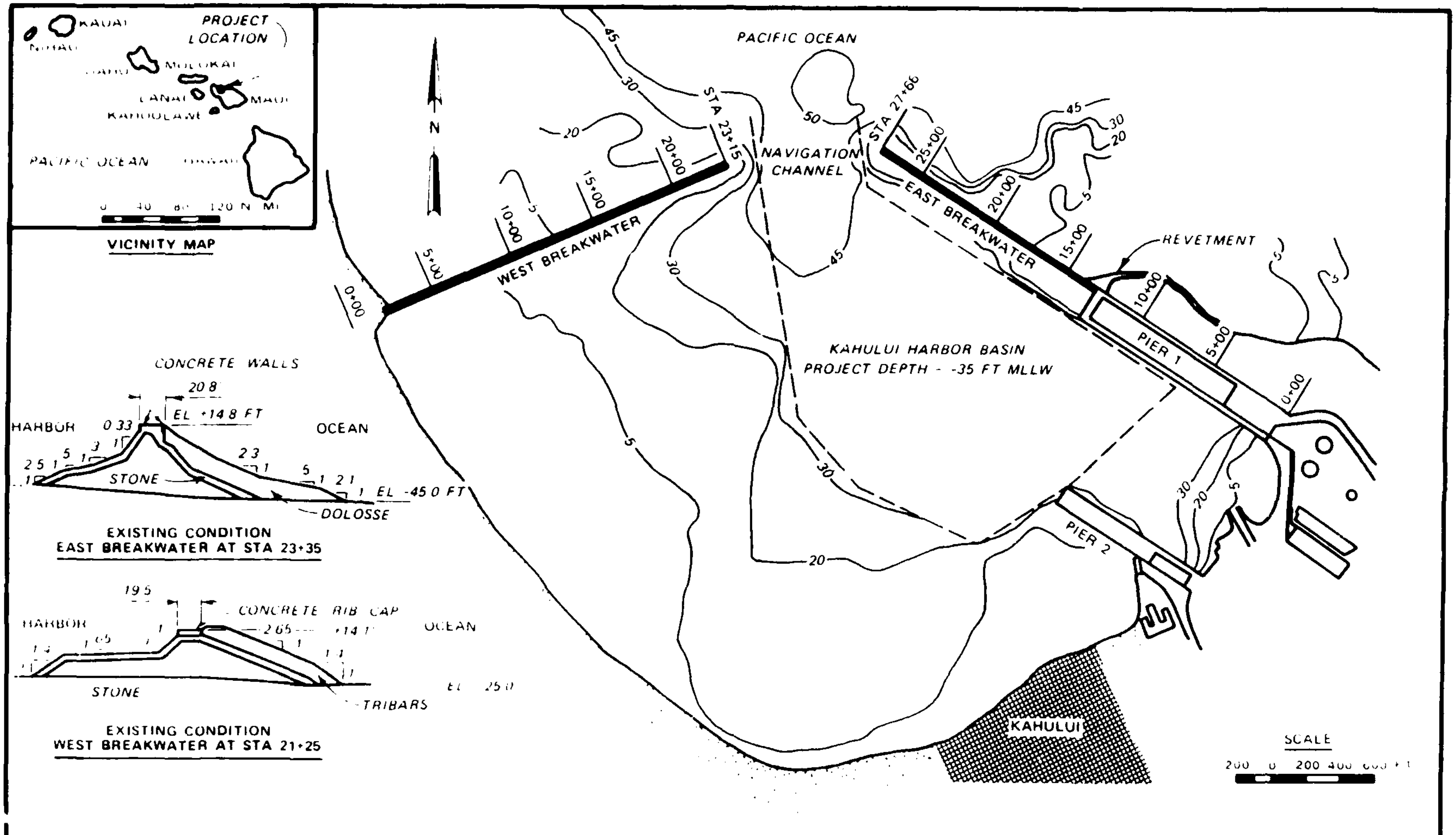
TYPICAL SECTION
CRESCENT CITY HARBOR BREAKWATER
1986 REHABILITATION
42-TON DOLOS



HILO HARBOR BREAKWATER LOCATION MAP

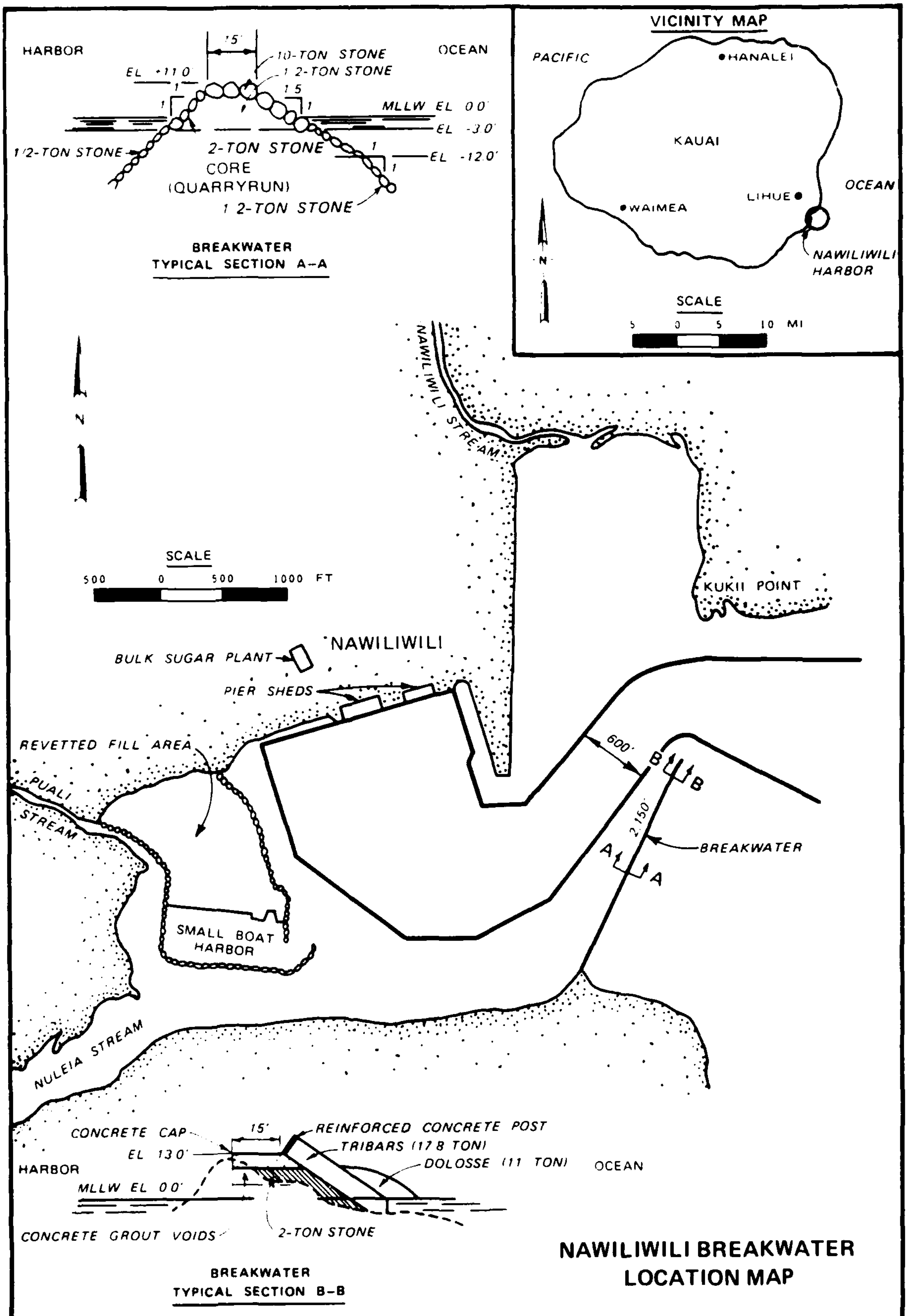


HUMBOLDT JETTIES LOCATION MAP

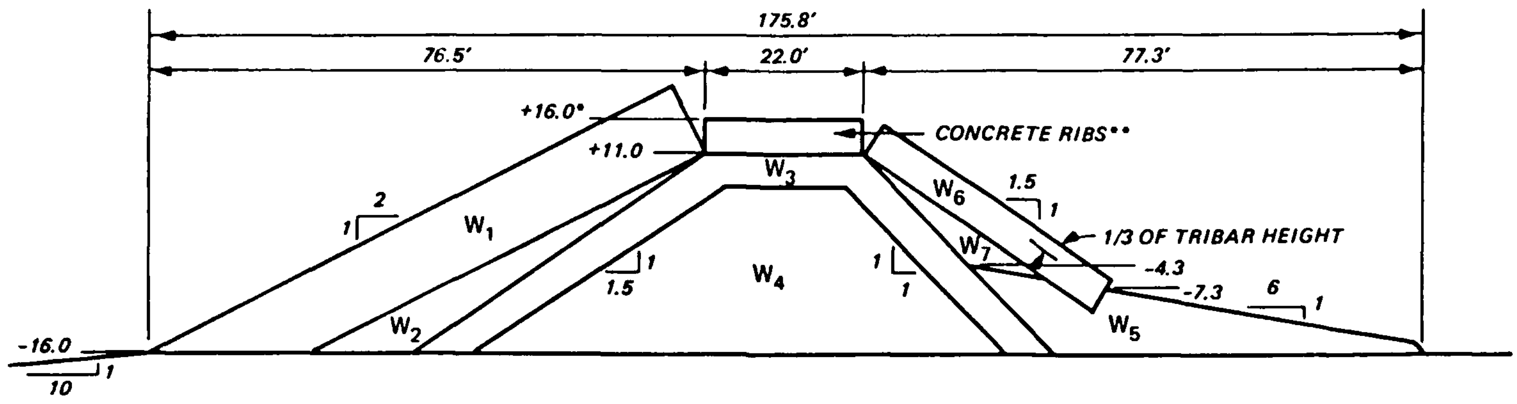


KAHULUI BREAKWATERS
LOCATION MAP

PLATE 10



NAWILIWILI BREAKWATER LOCATION MAP

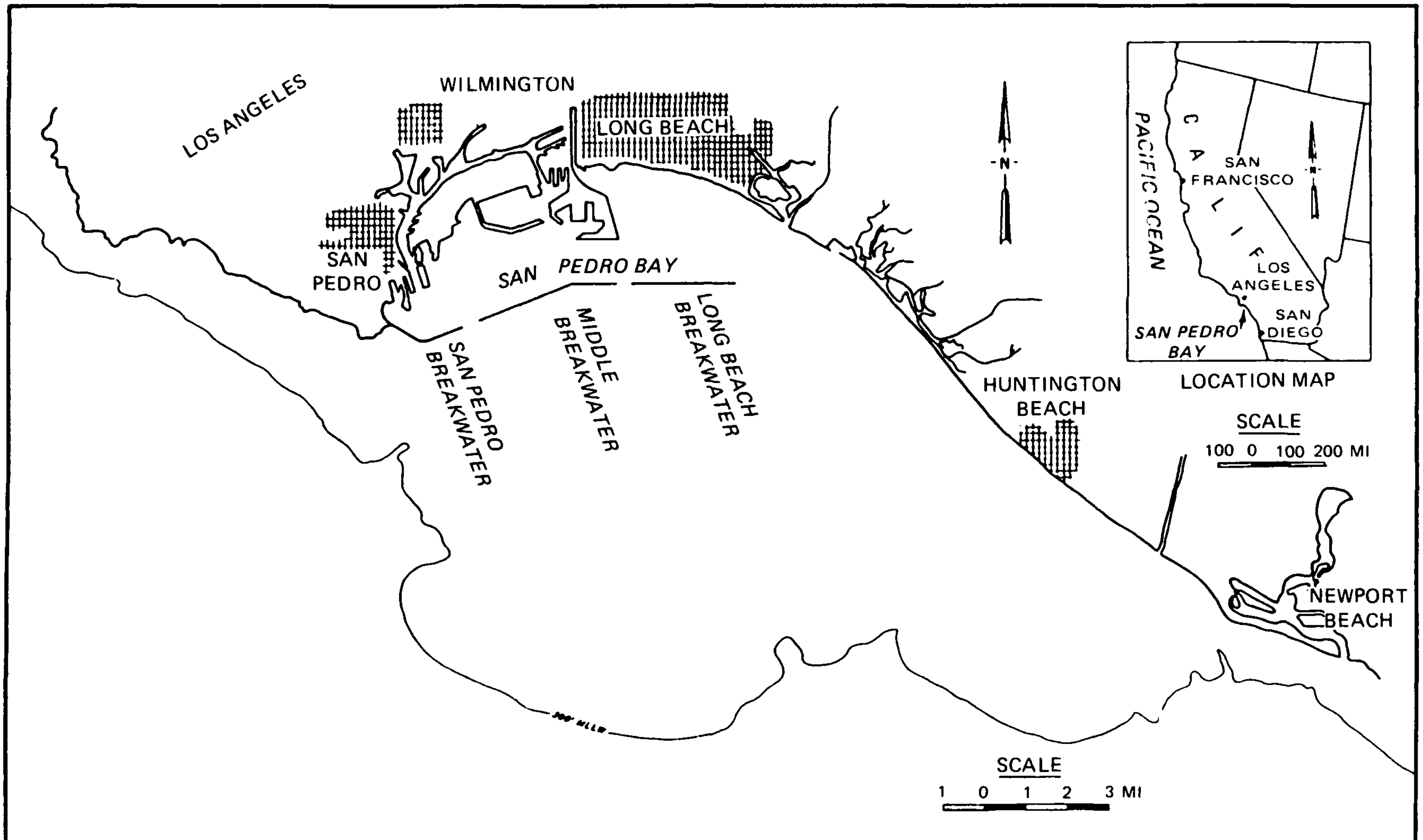


MATERIAL CHARACTERISTICS

W_1 = 11--TON DOLOSSE @ 146 PCF
W_2 = 1,000--LB TO 4,000-LB STONE @ 156 PCF
W_3 = 18,000--LB STONE @ 156 PCF
W_4 = 500--LB TO 2,000--LB STONE @ 156 PCF
W_5 = 13--LB TO 350--LB STONE @ 156 PCF
W_6 = 6.5--TON TRIBARS @ 146 PCF
W_7 = 1,000--LB TO 3,000-LB STONE @ 156 PCF

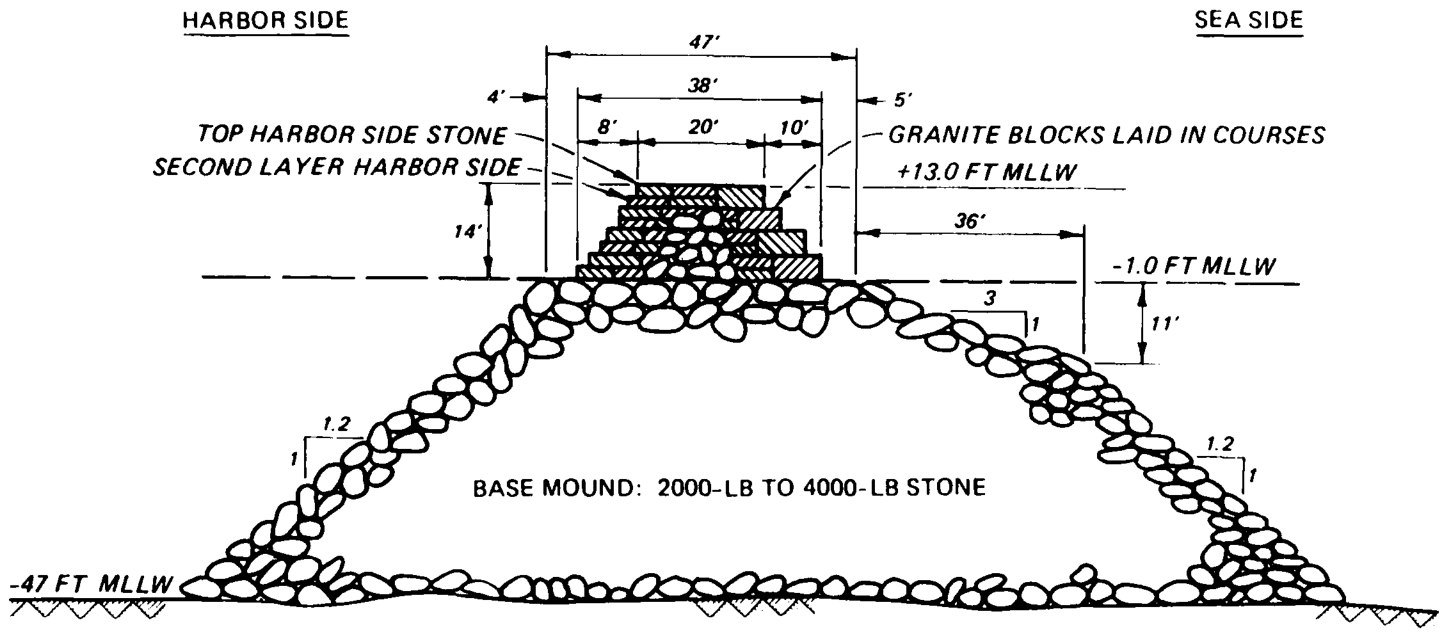
*ELEVATIONS IN FEET REFERRED TO MEAN LOWER LOW WATER

TYPICAL TRUNK SECTION
NAWILIWILI HARBOR BREAKWATER



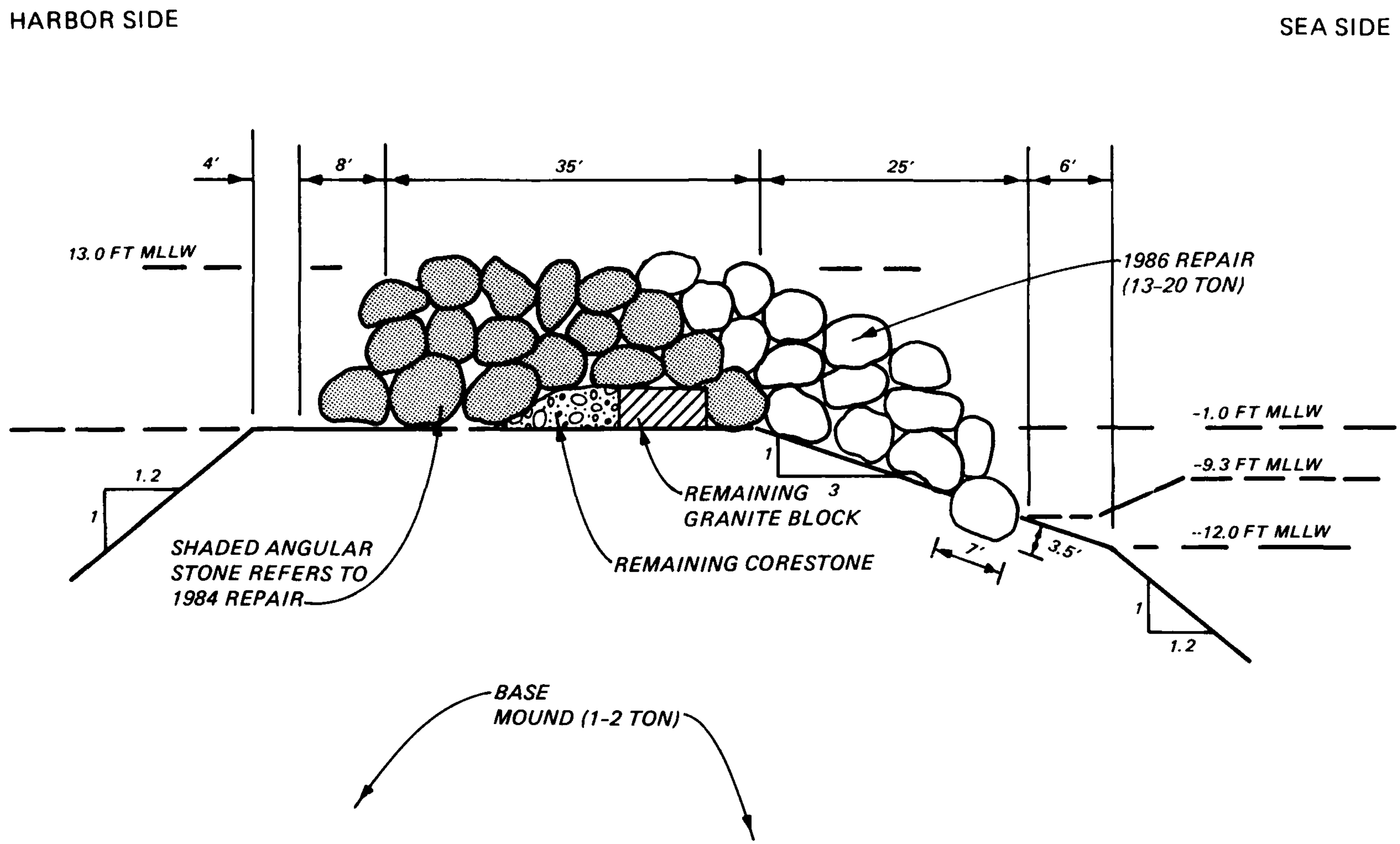
SAN PEDRO BREAKWATER
LOCATION MAP

PLATE 13



NOTE:
1. SEA-SIDE ARMOR STONE RANGES FROM 10 TO 12 TONS
2. HARBOR-SIDE ARMOR STONE RANGES FROM 5 TO 7 TONS
3. CORE MATERIAL PLACED ABOVE -1.0 FT MLLW RANGING FROM 10 TO 2,000 LB
4. UNIT WEIGHT OF STONE IS ASSUMED TO BE 165 PCF

TYPICAL SECTION
SAN PEDRO BREAKWATER



TYPICAL SECTION
SAN PEDRO BREAKWATER
1984 AND 1986 REPAIRS